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Confirmation of previous ground-based Cepheid P–L zero-points using *Hipparcos* trigonometric parallaxes

Allan Sandage[1] and G. A. Tammann[2]

[1] *The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101, USA*
[2] *Astronomisches Institut der Universitat Basel, Venusstrasse 7, CH-402 Binningen, Switzerland*

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ABSTRACT

Comparisons show agreement at the 0.1-mag level between the calibration of the Cepheid period–luminosity (P–L) relation by Feast & Catchpole (FC) using the early release of *Hipparcos* data and four previous ground-based calibrations, three of which are either largely or totally independent of the distance to the Large Magellanic Cloud (LMC). Each of the comparisons has the sense that the FC calibration is brighter, but only at the level of $\lesssim$0.1 mag. In contrast, FC argue that their *Hipparcos* recalibration leads to a 0.2-mag revision in the distance to the LMC, and thereby to a 10 per cent decrease in the Hubble constant. We argue differently. The comparison of the *Hipparcos* recalibration with others should be made using only local Galactic Cepheids, not based on Cepheids in the LMC that require a set of precepts that are not germane to the direct *Hipparcos* recalibration. The comparison made here, using only Galactic Cepheids, gives a correction of ~ 4 per cent or less to our value of H_0 based on Type Ia supernovae, keeping all other factors and precepts the same.

A second success of the *Hipparcos* mission is the calibration of the position of the main sequence in the Hertzsprung–Russell diagram as a function of metallicity using local subdwarfs. These data have been used by Reid and by Gratton et al. to obtain, similarly to FC, a brighter absolute magnitude of RR Lyrae stars by ~ 0.3 mag from that often currently adopted. These new calibrations confirm the earlier brighter calibrations by Walker, by Sandage, and by Mazzitelli, D'Antona & Caloi, thereby reducing the ages of globular clusters by ~ 30 per cent. This removes most of the cosmological time-scale problem if $H_0 \sim 55$ km s^{-1} Mpc^{-1}. A similar conclusion, based on pulsation theory and MACHO data, has been reached by Alcock et al.

Key words: Cepheids – distance scale.

1 INTRODUCTION

The early release of *Hipparcos* trigonometric parallax data on the distances of classical Cepheids has permitted Feast & Catchpole (1997, hereafter FC) to redetermine the zero-point of the Cepheid period–luminosity (P–L) relation in M_V. Of the 223 Galactic Cepheids in the *Hipparcos* Catalog, FC analysed the parallax data for the 26 nearest Cepheids that will contribute 75 per cent of the weight of the complete Cepheid list in an eventual definitive zero-point determination. Such a determination will take into account the intrinsic spread of the P–L correlation owing to the finite width of the instability strip, either by using colour data to determine where within the scatter a particular Cepheid lies, or by deriving a period–luminosity–colour (P–L–C) relation that accounts for this scatter (Sandage 1958, 1972). Nevertheless, from their preliminary analysis, FC have obtained a mean P–L relation that will define the ridge-line P–L relation within the intrinsic scatter if the 26 *Hipparcos* Cepheids of their sample form an adequate list with which to average out the scatter.

FC derive $M_V = -2.81 \log P - 1.43 \pm (0.10)$. We inquire how their analysis of the *Hipparcos* data compares with various previous ground-based determinations of the zero-point of the Cepheid P–L relation.

FC make the comparison of their *Hipparcos* calibration with that of Laney & Stobie (1994), with which they show disagreement at the 0.16- to 0.20-mag level, depending on the period. The *Hipparcos* zero-point is brighter. However, FC do not make comparisons with other Cepheid P–L relations, but rather use their derived *Hipparcos* calibration to obtain a new distance to the LMC from which they suggest a change in the Hubble constant by 10 per cent.

We argue here that, although interesting, this use of the LMC as an intermediary step is not only unnecessary, but also undesirable as a test of the effect of the *Hipparcos* Cepheid P–L zero-point alone on H_0.

Our first point is that the distance to the LMC can and should be ignored in the determination of distances to more distant galaxies, such as the parent galaxies containing Type Ia supernovae (SNe Ia). The method, independent of the distance to the LMC, is to use the Cepheid P–L relation directly (Sandage & Tammann 1996; Tammann 1996; Sandage et al. 1996; Saha et al. 1996, 1997) as calibrated using, for example, Galactic Cepheids in clusters and associations (Sandage & Tammann 1968; Feast & Walker 1987). No use need be made of the distance to Cepheids in the LMC in this calibration.[1] Precepts that have often been controversial are thereby avoided.

[1] In our Cepheid calibration of $\langle M(\max)\rangle_{\rm SNe\,Ia}$ (Saha et al. 1996, 1997) we have used the P–L relations in V and I by Madore & Freedman (1991) which *are* based on their assumption that $(m-M)_0=18.50$ for the LMC. However, the agreement to better than 0.1 mag of their P–L zero-point in V with the first three entries of Table 1 in Section 2, each of which contains no assumption of the LMC modulus, shows that our distance scale using Madore & Freedman's results is in fact independent of an assumption of the LMC distance at the $\sim$0.1-mag level.

Nevertheless, we are dependent on the Madore & Freedman zero-point in I. That zero-point is based on their LMC modulus coupled with their adopted mean $\langle E(V-I)\rangle_{\rm LMC}$ reddening. To the extent that this mean reddening is incorrect, their Cepheid zero-point in I will change. However, the LMC mean reddening is not in contention at the 0.03-mag level. Hence the possible effect of an error in the assumed LMC reddening on the P–L relation in I is also less than 0.1 mag. Eventually, of course, the P–L zero-point in I can be determined using I-band photometry of the calibrating Galactic Cepheids directly, independently of the LMC I-band data.

Our second point is to compare the *Hipparcos* Cepheid zero-point as derived by FC in V with several of the canonical P–L relations that have been proposed over the past four decades. These post-date Baade's (1952, 1956) major correction of 1.5 mag to Wilson's (1939) zero-point, which itself was close to the zero-point used by Hubble (1925, 1926, 1929) which was based on Hertzsprung (1913) as simply recalculated by Shapley (1918).

2 COMPARISON OF ZERO-POINTS OF VARIOUS P–L RELATIONS

Table 1 shows the comparison of the *Hipparcos* calibration with five previous calibrations of M_V, each read at a period of 10 d.

Although the agreement of five of the six entries in the table is impressive at the 0.1-mag level, a more detailed comparison is required over the relevant period range of $\log P$ between 0.6 and 1.6 to see better the effect of the FC recalibration via *Hipparcos* on our version of the extragalactic distance scale.

Table 2 shows this comparison for several of the entries in Table 1. We have used here the P–L relations listed by each of the indicated research groups. The four comparisons use the following equations, or their near-equivalents.

$$M_V = -2.83\log P - 1.40 \qquad (1)$$

Table 1. Absolute V magnitudes of Cepheids with $P=10$ d according to different P–L relations.

Source	$\langle M_V\rangle$ at 10 d
Kraft (1961)	−4.21
Sandage & Tammann (1968)	−4.20
Feast & Walker (1987)	−4.13
Madore & Freedman (1991)	−4.16
Laney & Stobie (1994)	−4.07
Feast & Catchpole (1997)	−4.24

Table 2. Comparison of M_V at various periods for four of the entries in Table 1.

log P (1)	M_V S/T (2)	M_V F/W (3)	M_V M/F (4)	M_V F/C (5)	S/T–F/C (6)	F/W–F/C (7)	M/F–F/C (8)
0.6	−3.12	−3.02	−3.06	−3.12	0.00	+0.10	+0.06
0.7	−3.38	−3.30	−3.33	−3.40	+0.02	+0.10	+0.07
0.8	−3.64	−3.57	−3.61	−3.68	+0.04	+0.11	+0.07
0.9	−3.92	−3.85	−3.88	−3.96	+0.04	+0.11	+0.08
1.0	−4.20	−4.13	−4.16	−4.24	+0.04	+0.11	+0.08
1.1	−4.50	−4.41	−4.44	−4.52	+0.02	+0.11	+0.08
1.2	−4.78	−4.69	−4.71	−4.80	+0.02	+0.11	+0.09
1.3	−5.06	−4.96	−4.99	−5.08	+0.02	+0.12	+0.09
1.4	−5.35	−5.24	−5.26	−5.36	+0.01	+0.12	+0.10
1.5	−5.64	−5.52	−5.54	−5.65	+0.01	+0.13	+0.11
1.6	−5.92	−5.80	−5.82	−5.93	+0.01	+0.13	+0.11
				mean	+0.021	+0.114	+0.085
				sd	0.014	0.010	0.016

approximates our early calibration (Sandage & Tammann 1968). The more precise statement of that calibration is set out in table A1 of that reference. Values from this table A1 are listed as S/T in Table 2.

The calibration of Feast & Walker (1987) is

$$M_V = -2.78 \log P - 1.35, \tag{2}$$

labelled F/W in the table.

One of the two calibrations set out by Madore & Freedman (1991) has the equation

$$M_V = -2.76 \log P - 1.40, \tag{3}$$

labelled M/F in Table 2.

The *Hipparcos* calibration by FC, stated above, is

$$M_V = -2.81 \log P - 1.43, \tag{4}$$

labelled F/C in Table 2.

The agreement of columns 2–4 with the *Hipparcos* result in column 5 is impressive. The best agreement is in column 2 compared with column 5. The differences between our S/T (1968) calibration and the F/C *Hipparcos* result of column 5 are listed in column 6. Equal weighting of the entries (as if the distribution of periods were flat) in column 6 gives a mean difference of 0.02 mag in the sense that the *Hipparcos* zero-point is brighter by this amount compared with our 1968 ground-based calibration.

The most important comparison for us is in column 8 between the calibration by Madore & Freedman (1991) and *Hipparcos*. This comparison is important because the M/F zero-point is the one that we have used throughout our *Hubble Space Telescope* (*HST*) Cepheid programme to calibrate $\langle M(\max)\rangle$ for SNe Ia. Our decision to adopt this zero-point was made because M/F also list a calibration of the *I*-band P–L relation, as well as the *V*-band one. We require both the *V*- and *I*-band data for the external galaxies to determine the reddening corrections to our apparent moduli of galaxies that contain the calibrating SNe Ia (see footnote 1).

3 CONSEQUENCES FOR THE HUBBLE CONSTANT

3.1 Direct consequences for the calibration via SNe Ia

As stated earlier, FC suggest that their *Hipparcos* result has a 10 per cent effect on those determinations of the Hubble constant that are based on an LMC modulus of $m - M = 18.50$. In this section we examine the effect of using the P–L relation directly in our SNe Ia calibrations which are independent of the LMC distance.

Had we used our S/T 1968 calibration of column 2 or equation (1) throughout our current *HST* calibration experiments, the new *Hipparcos* results would have required a decrease in our value of H_0 by 1 per cent, all other factors and precepts being kept the same.

However, our present calibration of $H_0 = 58 \pm 7$ km s^{-1} Mpc^{-1} via supernovae (Saha et al. 1997) must instead be decreased by 4 per cent, because, as said before, our P–L zero-point is based on equation (3) rather than on equation (1).

Hence, keeping all other factors and precepts constant, our present interim SNe Ia value of H_0 would be

$$H_0 = 56 \pm 7 \text{ km s}^{-1} \text{ Mpc}^{-1}, \tag{5}$$

using the FC *Hipparcos* calibration.

3.2 Comparison with others

It must be emphasized that the *Hipparcos* data as analysed by FC have no bearing on the difference by a factor of 1.25 between equation (5) and the value of $H_0 = 70$ km s^{-1} Mpc^{-1} (which is 73 reduced by 4 per cent via column 8 of Table 2) advocated by the *HST* Key Project consortium (Kennicutt, Freedman & Mould 1995; Freedman et al. 1996). *This* 25 per cent difference has its explanation in the different precepts concerning: (1) whether M100 defines the distance to the Virgo cluster core; (2) whether their discounting three of our six SNe Ia calibrators is justified and whether NGC 1365 defines the distances to both NGC 1316 and 1380 which have produced three SNe Ia in the Fornax cluster, thereby changing our calibration of $\langle M(\max)\rangle_{\rm SNe\,Ia}$ by ~ 0.5 mag; (3) whether the bias properties inherent in the Tully–Fisher method and its calibration have been adequately accounted for in its application to clusters and to field galaxies; and (4) whether the local velocity field can be adequately tied to the far cosmic expansion field by any methods other than those that directly calibrate objects such as SNe Ia and brightest cluster galaxies that themselves are in the far field (Sandage & Tammann 1990; Jerjen & Tammann 1993; Tammann & Sandage 1995). We have argued elsewhere (Sandage & Tammann 1996) that proper attention to these four problems in the Freedman et al. (1996) precepts gives a value of H_0 that is nearly identical to that in equation (5).

3.3 The time-scale calibration

FC also discuss the time-scale problem via the absolute magnitude of the RR Lyrae stars, by again going through the distance to the LMC, and the effect that any changes in this adopted distance have on the ages of globular clusters. As before, however, the distance to the LMC can be avoided via another route to the RR Lyrae star luminosities.

A second triumph of the *Hipparcos* mission is the recalibration of the position of the main sequence of the Hertzsprung–Russell (HR) diagram for subdwarfs of different metallicities. Using this recalibration of the subdwarf zero-age main sequence for different [Fe/H] values, Reid (1997) and Gratton et al. (1997) have redetermined, with similar, consistent results, the photometric parallaxes of a number of globular clusters (five in Reid and nine in Gratton et al.) that have a range of metallicities. They both have calibrated, thereby, the M_V/[Fe/H] absolute magnitude scale for RR Lyraes.

The calibration of Gratton et al. gives an absolute magnitude–metallicity relation for RR Lyrae stars over the range of [Fe/H] between $= -1.5$ and -2.2 that is even 0.06 mag brighter than the heretofore-controversial bright calibration of Sandage (1993b). That calibration was based on a model using pulsation theory and the precepts that are required to explain the Oosterhoff–Arp–Preston (OAP) RR Lyrae period–metallicity effect.

Reid's calibration also shows the required steep variation of M_V(RR) with [Fe/H] that is needed to explain the OAP effect. It has a zero-point in M_V that agrees with that of Sandage (1993a,b) at $[\mathrm{Fe/H}] = -1.5$. It is 0.18 mag brighter still at $[\mathrm{Fe/H}] = -2.2$.

A similar bright RR Lyrae calibration, based on pulsation properties of double-mode variables, and again agreeing with the bright calibration of Walker (1989, 1992) and Sandage (1993b), has also been derived by the MACHO collaboration (Alcock et al. 1997). These three recalibrations also agree with the most recent horizontal branch models of Mazzitelli, D'Antona & Caloi (1995) and Caloi, D'Antona & Mazzitelli (1997).

These brighter absolute magnitudes require that the ages of the Galactic globular cluster system be reduced to near 12 Gyr, where we have used the aforementioned horizontal branch models of Mazzitelli et al. and Caloi et al. The lower age for the Galactic globular system has been emphasized by each of the three groups (Reid 1997; Gratton et al. 1997; Alcock et al. 1997).

In summary, these early results from the *Hipparcos* mission show again that there is no 'time-scale crisis in big bang cosmology'. The inverse of equation (5) is $H_0^{-1} = 17.4 \pm 2$ Gyr. This would be the 'age of the Universe' if $\Omega = 0$ and $\Lambda = 0$, or, alternatively, $T_0 = 11.6 \pm 1.5$ Gyr if $\Omega = 1$. Hence this most basic time-scale test of the standard model using globular cluster ages (increased by 0.5 Gyr for the gestation period of the Galaxy) nearly satisfies the $\Omega = 1$ requirement of such a version of the model within the still-appreciable errors.

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